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Development of suitable photobioreactor for algae production – A review

R.N. Singh, Shaishav Sharma*

School of Energy and Environment Studies, Devi Ahilya Vishwa Vidyalaya, Takshashila Campus, Khandwa Road, Indore-452001, India

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ABSTRACT

Microalgal species are recently in the spotlight for biofuels production like biodiesel, bioethanol and biohydrogen. Algae are also used as a biofertiliser, source of nutrient and for controlling pollution. Algae being a photosynthetic organism are produced in the photo bioreactors. Hence the design and development of photobioreactors for maximum production of algae is very important. Apart from maximum production, other factors such as design, cost effectiveness of the bioreactor, purity of the algae produced, user friendly, low maintenance and space convenience need to be optimized. The bioreactors which are used for the purpose of growing algae are bubble column photobioreactor, airlift photo bioreactor, flat panel bioreactor, horizontal tubular photobioreactor, stirred tank photobioreactor etc. These bioreactors have their own advantages and disadvantages. Work is on for developing hybrid type of bioreactors which may overcome the limitations of the developed photobioreactors. This paper covers the salient features, limitations of developed photobioreactors and recent developments in the field of photobioreactors.

Contents

1. Introduction

Sustainability is a key principle in natural resource management, and it involves operational efficiency, minimization of environmental impact and socio-economic considerations; all of which are interdependent. It has become increasingly obvious that continued reliance on fossil fuel energy resources is unsustainable, owing to both depleting world reserves and the green house gas emissions associated with their use. Therefore, there are vigorous research initiatives aimed at developing alternative renewable and potentially carbon neutral solid, liquid and gaseous biofuels as alternative energy resources.

The growing consumption of fossil fuel, its adverse effects on the environment and 'Food v/s Fuel Controversy' aroused due to primary biofuels has caused a serious concern for scientists to develop alternative sources of fuel which do not cause adverse effect on environment as well as are efficient and cost effective.

* Corresponding author.
E-mail addresses: shaishav_bt@yahoo.co.in, shaishav.bt@gmail.com (S. Sharma).

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In contrast, second and third generation biofuel systems (such as lignocellulosic and microalgal biofuel systems) have the potential to overcome many of these limitations and target a newly emerging clean energy.

Therefore, based on current knowledge and technology projections, third generation biofuels specifically derived from microalgae are considered to be a technically viable alternative energy resource that is devoid of the major drawbacks associated with first and second generation biofuels. Microalgae are photosynthetic microorganisms with simple growing requirements (light, sugars, CO_2, N, P, and K) that can produce lipids, proteins and carbohydrates in large amounts over short periods of time. These products can be processed into both biofuels and valuable co-products.

This study reviewed the salient features, limitations of developed photobioreactors and recent developments in the field of photobioreactors for Algae production.

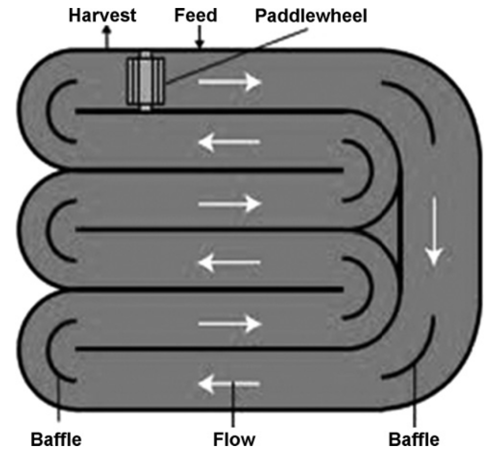

Fig. 1. Schematics of a raceway pond.

1.1. General characters of algae

Green algae and cyanobacteria (formally blue-green algae) comprise a vast group of photosynthetic organisms. Algae are some of the most robust organisms on earth, able to grow in a wide range of conditions. Algae are usually found in damp places or bodies of water and thus are common in terrestrial as well as aquatic environments [1]. It is distributed throughout the biosphere and grows in the widest possible range of conditions from aquatic (freshwater to extreme salinity) to terrestrial places. Algae lack the various structures that characterize land plants, such as phyllids (leaves) and rhizoids in nonvascular plants, or leaves, roots, and other organs that are found in tracheophytes (vascular plants). Its uniqueness that separates them from other microorganisms is due to presence of chlorophyll and having photosynthetic ability in a single algal cell, therefore allowing easy operation for biomass generation and effective genetic and metabolic research in a much shorter time period than conventional plants. Well defined nucleus, a cell wall, chloroplast containing chlorophyll and other pigments, pyrenoid, a dense region containing starch granules on its surface, stigma, and flagella are the major components of green algae [1]. Filamentous colonies of cyanobacteria have ability to differentiate into different cell types like vegetative cells, akinetes, and heterocysts. General function of vegetative cells, akinetes and heterocysts are ability to carry out complete oxygenic photosynthesis, resistance for climate and having a potential to fix nitrogen, respectively [2].

1.2. Algae cultivation methods

Cultivation of microalgae can be done in open systems (lakes, ponds) and in controlled closed systems called photo-bioreactors (PBR).

1.2.1. Cultivation of algae in ponds

Open pond systems are cheaper to construct, at the minimum requiring only a trench or pond. Large ponds have the largest production capacities relative to other systems of comparable cost. Also, open pond cultivation can exploit unusual conditions that suit only specific algae. For instance, *Spirulina* sp. thrives in water with a high concentration of sodium bicarbonate and *Dunaliella salina* grow in extremely salty water. Open culture can also work if there is a system of culling the desired algae and inoculating new ponds with a high starting concentration of the desired algae. The biggest advantage of these open ponds is their simplicity, resulting in low production costs and low operating costs [3]. Open ponds can be categorized into natural waters (lakes, lagoons, ponds) and artificial pond. The ponds in which the algae are cultivated are usually called the "raceway ponds" (Fig. 1). In these ponds, the algae, water and nutrients circulate around a racetrack. With paddlewheels providing the flow, algae are kept suspended in the water, and are circulated back to the surface on a regular frequency. The ponds are usually kept shallow because the algae need to be exposed to sunlight, and sunlight can only penetrate the pond water to a limited depth.

The raceways are typically made from poured concrete or they are simply dug into the earth and lined with a plastic liner to prevent the ground from soaking up the liquid. Baffles in the channel guide the flow around the bends in order to minimize space. The system is often operated in a continuous mode, where the fresh feed (containing nutrients including nitrogen phosphorus and inorganic salts) is added in front of the paddlewheel, and algal broth is harvested behind the paddlewheel after it has circulated through the loop. Depending on the nutrients required by algal species, several sources of waste water can be used for algal culture [4]. For some marine-type microalgae, seawater or water with high salinity can be used.While this is indeed the simplest of all the growing techniques, it has some drawbacks owing to the fact that the environment in and around the pond is not completely under control. Open ponds are highly vulnerable to contamination by other microorganisms, such as other algal species or bacteria. Thus cultivators usually choose closed systems for monocultures. Open systems also do not offer control over temperature and lighting [5]. The growing season is largely dependent on location and, aside from tropical areas, is limited to the warmer months. Bad weather can often stunt algal growth. However, major limitations in open ponds include uneven light intensity, evaporative losses, diffusion of CO_2 to the atmosphere, and requirement of large areas of land [6]. Furthermore, contamination by predators and other fast growing heterotrophs have restricted the commercial production of algae in open culture systems to only those organisms that can grow under extreme conditions. Also, due to inefficient stirring mechanisms in open cultivation systems, their mass transfer rates are very poor resulting to low biomass productivity [5].To overcome the problems associated with an open system, researchers have tried for closed ponds. Here the control over the environment is much better than that for the open ponds. Closed pond systems cost more than the open ponds, and considerably less than photobioreactors for similar areas of operation. As a variation of the open pond system, the idea behind the closed pond is to cover it off with a transparent or translucent barrier which turns it into a greenhouse. These closed systems are constructed using plexiglass. It allows more species to be grown; it allows the species that are being grown to stay dominant; and it extends the growing season – and if heated the pond can produce year round. It is also

possible to increase the amount of carbon-di-oxide in these quasi-closed systems, thus again increasing the rate of growth of algae.

2. Photobioreactors

A photobioreactor can be described as an enclosed, illuminated culture vessel designed for controlled biomass production. Photobioreactor refers to closed systems that are closed to the environment having no direct exchange of gases and contaminants with the environment. Photobioreactors, despite their costs, have several major advantages over open systems:

- Photobioreactors minimize contamination and allow axenic algal cultivation of monocultures.
- Photobioreactors offer better control over conditions such as pH, temperature, light, CO_2 concentration etc.
- Photobioreactors lead to less CO_2 loss.
- Photo bioreactors prevent water evaporation.
- Photobioreactors permit higher cell concentrations.
- Photobioreactors permit the production of complex biopharmaceuticals.

Tsoglin et al. [7] suggested following points to be taken into consideration while designing the photobioreactor:

- The reactor should permit the cultivation of various microalgal species universally.
- The reactor design must provide for the uniform illumination of the culture surface and the fast mass transfer of CO_2 and O_2.
- Cells of microalgae are highly adhesive which results in rapid fouling of the light transmitting surfaces of reactors. This leads to frequent shutdown of the reactors for mechanical cleaning and sterilization. The reactor design must prevent or minimize the fouling of the reactor, particularly of its light transmitting surfaces.
- High rates of mass transfer must be attained by means that neither damage cultured cells nor suppress their growth.
- Photobioreactor must work under conditions of intense foaming, as often occurs in reactors with high rates of mass transfer.
- The reactor should have minimum non-illuminated part.

Different types of photobioreactors have been designed and developed for the production of algae.

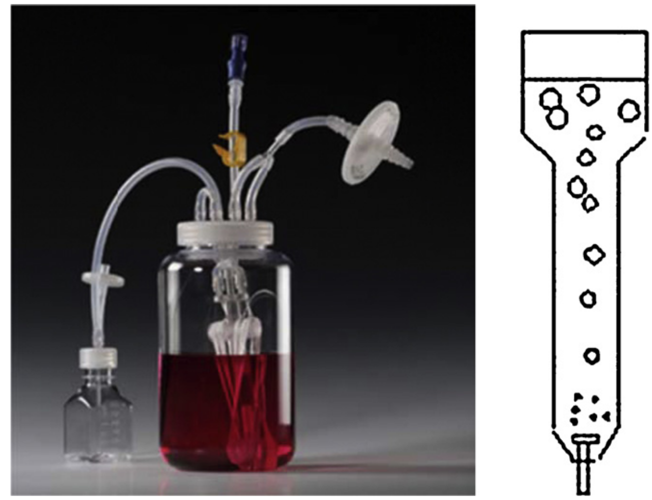

Fig. 2. Photograph and schematics of bubble column reactor.

2.1. Vertical tubular photobioreactor

It is made up of vertical tubing that is transparent in nature to allow the penetration of light. Sparger is attached at the bottom of the reactor which converts the sparged gas into tiny bubbles.

Sparging with gas mixture provides overall mixing, mass transfer of CO_2 and also removes O_2 produced during photosynthesis [2]. Vertical tubular photobioreactors can be divided into bubble column and airlift reactor based on their mode of liquid flow.

2.1.1. Bubble column photobioreactor

Bubble column reactors are cylindrical vessel with height greater than twice the diameter. It has advantage of low capital cost, high surface area to volume ratio, lack of moving parts, satisfactory heat and mass transfer, relatively homogenous culture environment, efficient release of O_2 and residual gas mixture. Mixing and CO_2 mass transfer is done through bubbling the gas mixture from sparger (Fig. 2). In scale-up, perforated plates are used in tall bubble column to break up and redistribute coalesced bubbles [8]. Light is provided externally. Photosynthetic efficiency greatly depends on gas flow rate which depends on the light and dark cycle as the liquid circulated regularly from central dark zone to external photic zone at higher gas flow rate. At gas flow rate less than 60.01 m s^{-1}

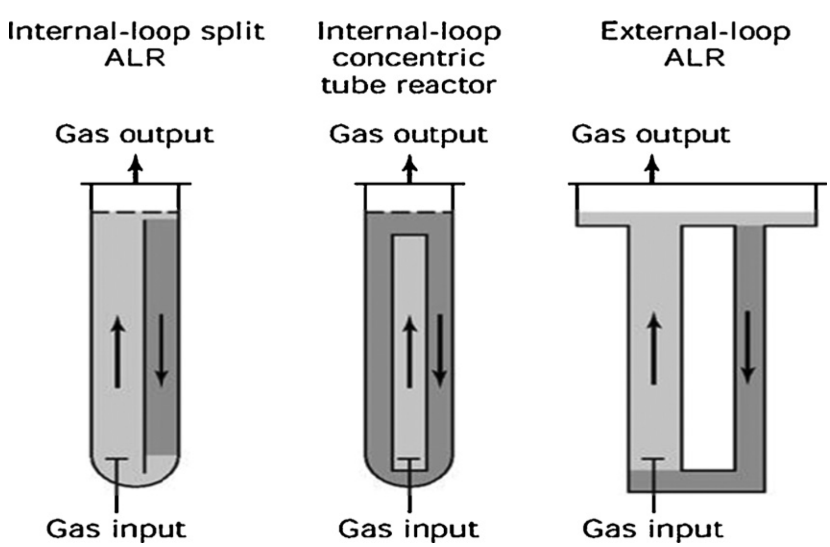

Fig. 3. Different types of air lift bioreactors.

circulation flow pattern does not exist because of the absence of back mixing [9]. The photosynthetic efficiency can be increased significantly by increasing the gas flow rate leading to shorter light and dark cycle.

2.1.2. Airlift photobioreactor

Airlift reactors are vessel with two interconnecting zones. One of the tubes is called riser where gas mixture is sparged whereas the other region is called downcomer which does not receive the gas (Fig. 3). Generally it exists in two forms – internal loop and external loop. In the internal loop reactor, regions are separated either by a draft tube or a split-cylinder. Internal loop reactor has been modified into internal loop split airlift reactor and internal loop concentric tube reactor. In the external loop, riser and downcomer is separated physically by two different tubes. Mixing is done by bubbling the gas through sparger in the riser tube without any physical agitation. Riser is similar to bubble column where sparged gas moves upward randomly and haphazardly. This decreases the density of the riser making the liquid to move upward. This upward movement is assisted by the gas hold up of riser. In the disengagement zone gas leaves the liquid and its performance depends upon design of this section and the operating conditions. The amount of gas which does not disengage in the disengagement zone gets trapped by liquid moving downward in the downcomer. Gas hold up in the downcomer has a significant influence in the fluid dynamics of the airlift reactor. Degassed liquid moves downwards in the annular space in laminar fashion with defined and oriented motion. Increasing the gas hold-up difference between riser and downcomer is important criteria to take into account while designing airlift reactor. Airlift reactor has characteristics advantage of creating circular mixing pattern where liquid culture passes continuously through dark and light phase giving flashing light effect to algal cells [10]. Residence time of gas in various zone controls performance affecting parameters like gas–liquid mass transfer, heat transfer, mixing and turbulence. It has been modified into many shapes like putting sparger into annular tube. Rectangular airlift photobioreactor is also suggested having better mixing characteristics and also the high photosynthetic efficiency but the disadvantage is its complexity and difficulty in scale-up [9]. An airlift photobioreactor with external loop has been designed by Loubiere et al. [11] which produce swirling motion.

2.2. Flat panel photobioreactor

The flat panel reactor has cuboidal shape with minimal light path (Fig. 4). It can be made from transparent materials like glass, plexiglass, polycarbonate etc. It is characterized by high surface area to volume ratio and open gas disengagement systems. Agitation is provided either by bubbling air from its one side through perforated tube or by rotating it mechanically through motor.

A flat panel was built up by Barbosa et al. [12] from lexan (polycarbonate) held together in stainless steel having surface area to volume ratio of 0.34 cm^{-1}.The mixture of CO_2 and air was sparged through 17 needles with a diameter of 0.8 mm pinched through a piece of silicon placed at the bottom of the reactor. The reactor was illuminated at one surface with 10 fluorescent tubes having total light intensity of approximately 1000 μmol photons $m^{-2}\,s^{-1}$ [12]. It was modified by Zhang et al. [13] by inclusion of baffles to improve agitation. Iqbal et al. [14] modified flat panel reactor by including some more engineering features like giving it V shape to achieve high mixing rate, eliminating escape corners which minimizes shear stress and cell adhesion to the walls of the reactor. Tredici and Zittelli [15] designed near horizontal flat panel which was divided longitudinally into five channels with two plexiglass manifolds at the top and at the bottom. Surface area to volume ratio was 40 m^{-1} with gas hold up capacity of 10.3%. Carbon dioxide gas mixture was injected axially through the bottom tubular plexiglass manifolds. It had photosynthetic efficiency of 4.8% less compared to inclined tubular reactor (5.6%) when kept outdoor using *Arthrospira* (*Spirulina*) *platensis M2*. It may be due to that curved surface of later, which reduces the light saturation effect at midday [15]. In a continuous culture of *Chlorella sorokiniana* using flat panel having short path length under high irradiance condition volumetric productivity obtained was 12.2 g $L^{-1}\,d^{-1}$. It was highest productivity of green algae so far discovered under over-saturating light condition [16]. It can be scaled up by arranging several plates over an area. Lengthening the reactor is not recommended for scale-up rather increase in liquid height and widening the light path is the recommended solution of scale-up [17]. Flat panel designed by Degen et al. [18] had the airlift mode of circulation. It had smaller downcomer zone and large riser zone where compressed air was injected. In addition, baffles were the other features of their reactor which was attached alternatively to the front and back of the larger faces of the panel.

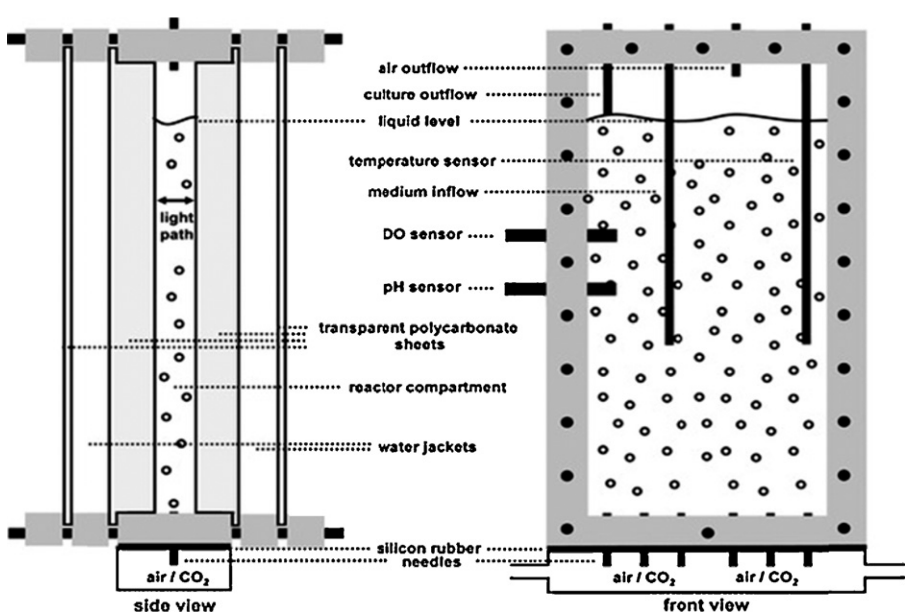

Fig. 4. Front and side view of the flat panel photobioreactor.

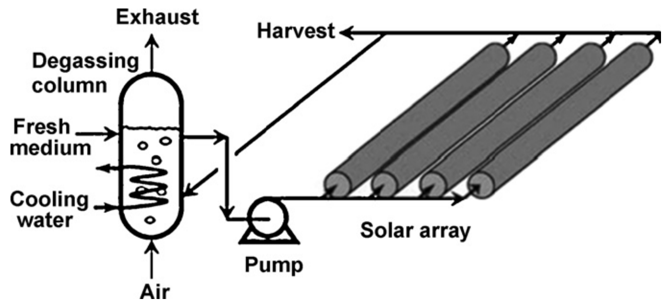

Fig. 5. Working of a horizontal tubular photobioreactor.

Transparent cooling jacket was also attached on the front illuminated side of the reactor. Volumetric mass productivity was 1.7 times higher than a similar bubble column reactor.

2.3. Horizontal tubular photobioreactor

Horizontal tubular reactors are placed horizontally giving the design of parallel set of tubes, loop shape, α shape, inclined tubular shape or horizontal tubular reactor (Fig. 5). Its shape gives advantage in outdoor culture for their orientation towards sunlight resulting in high light conversion efficiency.

CO_2 gas mixture is introduced into the tube connection via a dedicated gas exchange system. Oxygen build up during photosynthesis causes photo bleaching and reduces the photosynthetic efficiency [19]. Methods adapted for cooling of the system has been spraying water on the surface of the tubes, overlapping of tubes, placing the light harvesting unit inside a pool of temperature controlled water, and regulating the temperature of feed or recirculation stream. Another major drawback is the high energy consumption of about 2000 W m^{-3} compared with 50 W m^{-3} for bubble column and flat plate photobioreactors. This high energy input is necessary to reach high linear liquid velocities of about 20–50 m s^{-1} for achieving turbulent conditions with sufficient short light/dark cycles [20]. The inclined tubular is similar to the horizontal tubular reactor; however it has inclination of few degrees towards the sun. This inclination helps in harnessing sun light more efficiently. Reactor designed by Tredici and Zittelli [15] was made up of plexiglass tubes having 3.4 cm internal diameter placed side by side without any space between tubes. Tubes were connected at top and bottom ends by tubular plexiglass manifolds. It was laid on a wooden framework facing south with an angle of 5° horizontally [15]. Surface area to volume ratio was maintained 70 m^{-1}, however gas holdup was kept 10.3% of total volume occupied by the gas bubbles. Automatic evaporative cooling system was used for maintaining the temperature control. Volumetric productivity and photosynthetic efficiency was higher than flat reactor.

2.4. Helical type photobioreactor

Helical type photobioreactor consists of coiled transparent and flexible tube of small diameter with separate or attached degassing unit. A centrifugal pump is used to drive the culture through long tube to the degassing unit (Fig. 6).

Travieso et al. [21] experimented with this system with different algal strains. CO_2 gas mixture and culture medium can be circulated from either direction but injection from bottom gives better photosynthetic efficiency [22].

Tredici and Zittelli [15] designed coiled type photobioreactor with PVC having 3 cm diameter wound on a rigid vertical structure with an inclination of 2° with horizontal. It was provided with degasser to remove the produced oxygen and remaining residual gas of injected gas stream. Volumetric productivity and photosynthetic efficiency was found to be 0.9 g L^{-1} d^{-1} and 6.6%, respectively. Light dilution effect, use of diffusive radiation plus light absorbing capacity of PVC are responsible for its higher photosynthetic efficiency. It had surface area to volume ratio of 53 m^{-1} with 23% of total volume was occupied by the gas bubbles [15]. Its advantage included long tubes placed at small rise occupying small ground area, better CO_2 transfer from gas phase to liquid phase due to large CO_2 absorbing pathway [23]. Although scale-up can be done by simply adding light harvesting unit but the energy required by centrifugal pump in recirculating the culture and associated shear stress limits its commercial use. Fouling on the inside of the reactor is another disadvantage of this system. Morita et al. [24] gave the cone shape to the helical photobioreactor with a cone angle of 60°. The angle and height are strictly defined for conical helical system. Conical helical reactor was made-up of PVC tubing coiled in a conical framework. Air pump was used for the recirculation of the liquid. This system was also having attached degassing system and heat exchanger to control the temperature. At an angle of 60° photoreceiving area and hence photosynthetic productivities increases by a factor of two. Photosynthetic efficiency of 6.84% was greatest among all other cone angle tested for this reactor. Direction of injection of gas was tested from either direction with 10% (v/v) CO_2 and maximum photosynthetic efficiency of 6.25% was found when gas was circulated through bottom of this reactor. The main advantage of cone shape is the light harvesting efficiency with the same basal area [25]. Photobioreactor has advantage with respect to balance between energy input and photosynthetic efficiency. Less energy requirement for its operation and less mechanical stress imposed to algal cells are the other advantages of this reactor. Increasing the number of light harvesting units was the only way for scale-up because of its defined angle and size but it leads to larger energy loss in the complicated branches of the flow networks.

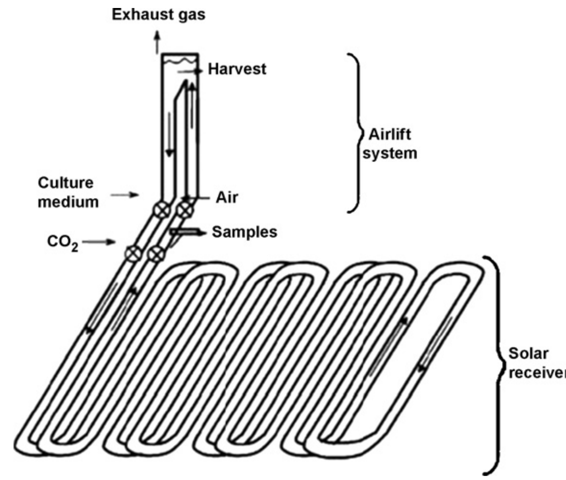

Fig. 6. Helical type photobioreactor.

2.5. Stirred tank photobioreactor

Stirred tank reactor is most conventional where agitation is provided mechanically with the help of impeller of different sizes and shapes. Baffles are used in order to reduce vortex (Fig. 7). CO_2 enriched air is bubbled at the bottom to provide carbon source for the growth of algae. This type of bioreactor has been turned into photobioreactor by illuminating it externally by fluorescent lamps or optical fibers but the main disadvantage of this system is low surface area to volume ratio which in turn decreases light harvesting efficiency. Use of optical fibers has been also tried but the use of optical fibers for illumination has disadvantage because of its hindrance in the mixing pattern. New Brunswick Bioflo 115

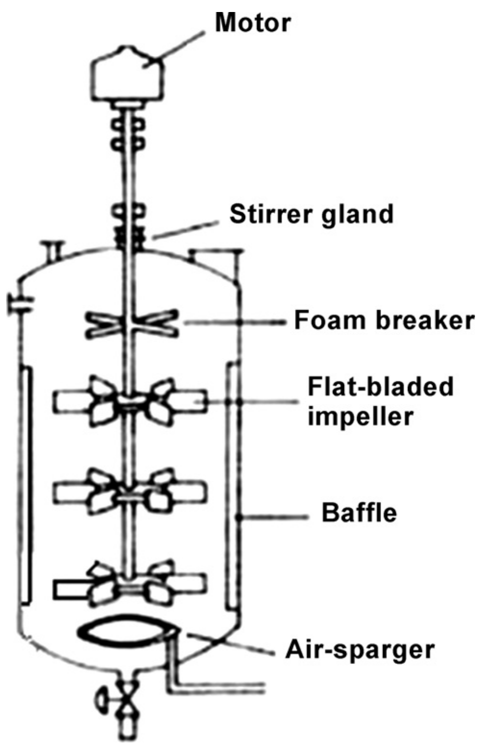

Fig. 7. Stirred Tank Photobioreactor.

and Bioengineering fermentors are commercially available photobioreactor having external light systems [2]. Large disengagement zone separates the unused sparged gas and produced oxygen during photosynthesis from gassed liquid to gas phase.

2.6. Hybrid type photobioreactor

Hybrid type of photobioreactor is widely used which exploits the advantages of the two different types of reactor and one overcomes the disadvantage of other. Fernandez et al. [26] has used integrated airlift system and external tubular loop placed horizontally in a thermostatic pond of water. Reactor had total volume of 200 L. On one hand external loop acts like light harvesting unit as it gives high surface area to volume ratio and controls the temperature of the culture. On the other hand airlift system acts as a degassing system where probes can also be integrated in order to regulate the other culture variables. Its advantage includes better control over culture variables, enabling higher productivities and reducing power consumption [26]. Grima et al. [27] and Richmond et al. [28] have developed similar type of integrated system but the external light harvesting unit of former was horizontal parallel sets of tubes different from loop like structure developed by later. Temperature was controlled by former using spray of water over the external light harvesting unit. Advantage of horizontal tubes was its photosynthetic efficiency and the low cost. The main disadvantage was large occupied land area and very narrow light harvesting unit. It is not economically feasible because of the cost associated with required land area and bundle of tubes. The α-shaped reactor is another type of hybrid system developed by Lee et al. [29] and designed and constructed based on algal physiology and sunlight. In this reactor, the culture is lifted 5 m by air to a receiver tank and culture flows down an inclined PVC tube (2.5 cm ID $\times$ 25 m) making 25° with the horizontal to reach another set of air riser tubes and the process repeated for the next set of tubes. The unidirectional and high liquid flow rate can be achieved at relatively low air flow rates. Also due to large area to volume ratio, photosynthetic efficiency is high.

2.7. Promising bioreactors

The major advantages associated with the bubble column bioreactor are its low capital costs, high surface area to volume ratio, lack of moving parts, satisfactory heat and mass transfer, efficient release of O_2 and residual gas mixture. The flat panel bioreactor's modification reported highest productivity under over saturating light conditions. Volumetric mass productivity was 1.7 times higher than that of similar bubble column reactor. The shape of horizontal tubular bioreactor is advantageous in outdoor culture for their orientation towards light resulting in high light converting efficiency. Also the photosynthetic efficiency and volumetric productivity was higher than that of flat panel bioreactor. Helical type photobioreactor also have edge over other bioreactors because of low land requirement, better CO_2 transfer from gas phase to liquid phase but the major disadvantage of this reactor is the fouling inside the reactor and energy required by centrifugal pump in recirculating culture and associated shear stress which limits its commercial use.

2.8. Recent developments

An experimental helical-tubular photobioreactor has been designed by Briassoulis et al. [30] for controlled, continuous production of Nanochloropsis species. Its main advantages includes: combination of large ratio of culture volume to surface area along with the optimized light penetration depth, easy control of temperature and contaminants, effective spatial distribution of fresh air and CO_2, better CO_2 transfer through extensive interface surface between fresh air and culture-liquid medium and novel automated flow-through sensor providing continuous cell concentration monitoring.Henrard et al. [31] evaluated the potential of semicontinuous cultivation of Cyanobium species in closed tubular bioreactor, combining factors such as blend concentration, renewal rate, and sodium bicarbonate concentration. Cultivation was carried out in vertical tubular photobioreactor for 2 L, in 57 d, at 30 °C, 3200 Lux, and 12 h light/dark photoperiod. The maximum specific growth rate was found as $0.127\,d^{-1}$, when the culture had blend concentration of $1.0\,g\,L^{-1}$, renewal rate of 50%, and sodium bicarbonate concentration of $1.0\,g\,L^{-1}$. The maximum values of productivity ($0.071\,g\,L^{-1}\,d^{-1}$) and number of cycles (10) were observed in blend concentration of $1.0\,g\,L^{-1}$, renewal rate of 30%, and bicarbonate concentration of $1.0\,g\,L^{-1}$. The results showed the potential of semicontinuous cultivation of *Cyanobium* species in closed tubular bioreactor, combining factors such as blend concentration, renewal rate, and sodium bicarbonate concentration.

Results of hydrodynamic and mass transfer characterization of a flat-panel airlift photobioreactor with high light path indicate that the hydrodynamic and mass transfer characteristics of this photobioreactor are more efficient than those reported elsewhere for tubular and other flat-plate photobioreactors, which opens the possibility of using photobioreactors with higher light paths than yet proposed [32].

Janssen et al. [9] studied light regime, photosynthetic efficiency, scale-up, and future prospects of enclosed outdoor photobioreactors. In this study it is shown that productivity of photobioreactors is determined by the light regime inside the bioreactors. In addition to light regime, oxygen accumulation and shear stress limit productivity in certain designs. In short light-path systems, high efficiencies, 10–20% based on photosynthetic active radiation (PAR 400–700 nm), can be reached at high biomass concentrations (>5 kg [dry weight] m^{-3}). It is demonstrated, however, that these and other photobioreactor designs are poorly scalable (maximal unit size 0.1–10 m^3) and/or not applicable for cultivation of

monocultures. This is why a new photobioreactor design is proposed in which light capture is physically separated from photoautotrophic cultivation. This system can possibly be scaled to larger unit sizes, 10 to >100 m^3, and the reactor liquid as a whole is mixed and aerated. It is deduced that high photosynthetic efficiencies, 15% on a PAR-basis, can be achieved. Future designs from optical engineers should be used to collect, concentrate, and transport sunlight, followed by redistribution in a large-scale photobioreactor. The research co-operation project between The Norwegian Institute for Agricultural and Environmental research in Norway, Uppsala University in Sweden and IIT Kharagpur in India, the $BioCO_2$ project (2008–2011), has designed, constructed and tested a flat panel, rocking photobioreactor for algae cultivation (nonrocking mode) and hydrogen production (rocking mode). It consists of two glass plates fixed between an inner frame made of stainless steel and outer frames made of aluminium, an air bubbling tube and a tube designed for temperature regulation [33].

3. Conclusion

Developed bioreactor requires detail knowledge of light distribution, mass transfer, shear stress, scalability and biology of algae cells. None of the single bioreactor fulfills all the requirements of a complete bioreactor. However, hybrid reactors have proved to be useful in mass production of algae as compared to single bioreactors. Efforts may be made to combine different types of bioreactors to develop suitable bioreactors for mass algal culture.

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